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# Plant density and leaf morphology affects yield, fiber quality, and nutrition of cotton[1]

## Densidade de plantas e morfologia foliar afetam a produtividade, qualidade e nutrição do algodoeiro

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*HIGHLIGHTS:*
*High plant density does not improve cotton yield.*
*The highest yield is obtained with the conventional leaf cultivar, regardless of plant density.*
*Fiber strength and length are higher in conventional leaf cultivar.*

**ABSTRACT:** In sandy soils with frequent drought events, the choice of cultivar and plant density is crucial to improve water use efficiency and avoid losses in cotton yield and fiber quality. This study aimed to evaluate cotton cultivars' yield and fiber quality at different plant densities. The study was carried out during two growing seasons (2017/2018 and 2018/2019) on sandy soil in southeastern Brazil. The cultivar TMG 47B2RF showed 27 and 29% higher yields under low and medium plant density, respectively, when compared with the highest plant density. The higher yield was due to the higher number of bolls in relation to the cultivar DBB 509B2RF. The boll weight of cultivar DBB 509B2RF was 23 and 22% higher under low and medium plant density, respectively. Fiber length and strength were higher in TMG 47B2RF compared to DBB 509B2RF. The leaf nutrient content was higher in DBB 509B2RF, except for Ca and Mg. When there is a regular rainfall, the low plant density results in higher yields, but intermediate plant density is the best option in cropping seasons with severe drought. The high density of plants in sandy soil environments was never a better option for none of the cultivars.

**Key words:** leaf morphology, cultivars, plant nutrition, fiber strength

**RESUMO:** Em solos arenosos com secas frequentes, a escolha da cultivar e densidade de plantas é fundamental para melhorar a eficiência do uso da água e evitar perdas na produtividade e qualidade da fibra do algodão. Objetivou-se avaliar a produtividade e a qualidade da fibra de cultivares de algodão em diferentes densidades de plantas. O estudo foi realizado em duas safras (2017/2018 e 2018/2019) em solo arenoso no sudeste do Brasil. A cultivar TMG 47B2RF teve produtividade 27 e 29% maiores sob baixa e média densidade de plantas, respectivamente, em comparação com a maior densidade de plantas. A maior produtividade deveu-se ao maior número de capulhos em relação à cultivar DBB 509B2RF. O peso dos capulhos da cultivar DBB 509B2RF foi 23 e 22% maior em baixa e média densidade, respectivamente. O comprimento e a resistência da fibra foram maiores com a cultivar TMG 47B2RF comparado com a cultivar DBB 509B2RF. O teor de nutrientes nas folhas foi maior no DBB 509B2RF, exceto Ca e Mg. Quando há chuvas regulares, a baixa densidade de plantas resulta em maiores produtividades, mas a densidade intermediária de plantas é a melhor opção em safras com seca severa. Alta densidade de plantas em ambientes de solo arenoso não foi a melhor opção para nenhuma das cultivares.

**Palavras-chave:** morfologia foliar, cultivares, nutrição de plantas, resistência das fibras

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## Introduction

Cotton is frequently cultivated in sandy soil subject to water deficit, where yields are usually lower, especially in dry cropping seasons (Cordeiro et al., 2022). An option to improve cotton yield in these challenging environments is the choice of plant density and cultivar (Galdi et al., 2022). Reducing plant density decreases canopy transpiration, increasing water use efficiency even under irrigation conditions (Chen et al., 2019).

Due to the high technology on board, the cost of cotton seeds is high. Based on this, recent studies evaluated the influence of reducing plant density (Adams et al., 2019; Chapepa et al., 2020). In Brazil, plant density ranges from 50,000 to 100,000 plants $ha^{-1}$ (Galdi et al., 2022). Mostly Brazilian cotton is produced in environments with medium-textured and clayey soils, with high rainfall during the cycle (Galdi et al., 2022).

Cotton leaf morphology varies from highly divided (okra leaf) to normal leaf (conventional leaf) (Gonias et al., 2011). Okra leaf cultivars have smaller leaf areas, are more effective in leaf cooling, release heat (Leigh et al., 2017), and have greater water use efficiency. Increasing plant density decreases the boll weight, decreasing the net assimilation rate (Zhang et al., 2016). Low or high plant density impairs the formation of reproductive structures, decreasing boll filling (Mao et al., 2015) and fiber yield (Yao et al., 2016). Cultivars and different plant densities can affect nutrient uptake by cotton and fiber quality (Khan et al., 2019). The yield of okra and conventional leaf cultivars did not differ (Bourland & Jones, 2018) in clayey soil. However, the impact of water restriction on okra leaf cultivars in sandy soils remains unknown.

We hypothesized that testing a cotton cultivar with okra leaf performs better than conventional leaves under high plant density in an environment with sandy soil and water deficit. This study aimed to evaluate cotton cultivars' yield and fiber quality at different plant densities.

## Material and Methods

The study was conducted in the 2017/2018 and 2018/2019 crop seasons (November to April) in Presidente Bernardes, State of São Paulo, Brazil (22° 11' 53" S, 51° 40' 30" W, at 401 amsl) in a soil classified as Oxisols of sandy texture. The chemical characteristics of the soil before planting are described in Table 1. The region has a tropical climate with dry winters (Aw - Köppen). The average of the maximum and minimum temperatures and precipitation during the two crop seasons of the experiment are shown in Figures 1A and B. The solar radiation and vapor pressure deficit during the experiment are shown in Figures 2A and B.

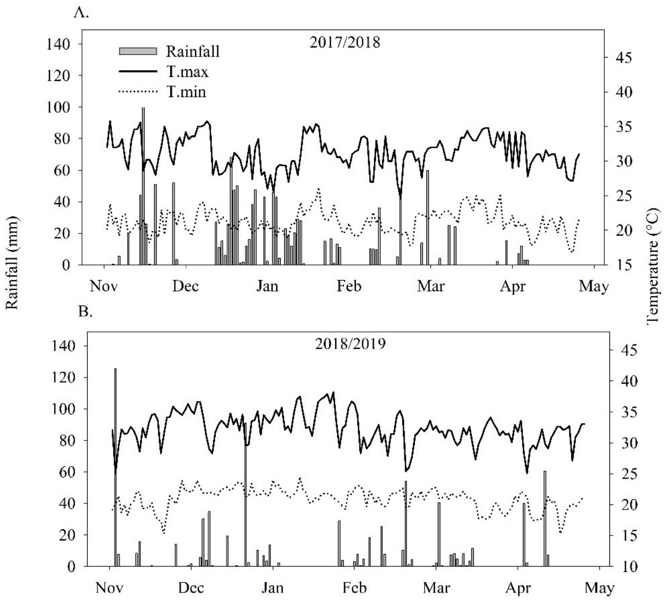



**Figure 1.** Rainfall and daily maximum and minimum temperatures during the cotton growing season in 2017/2018 (A) and 2018/2019 (B)

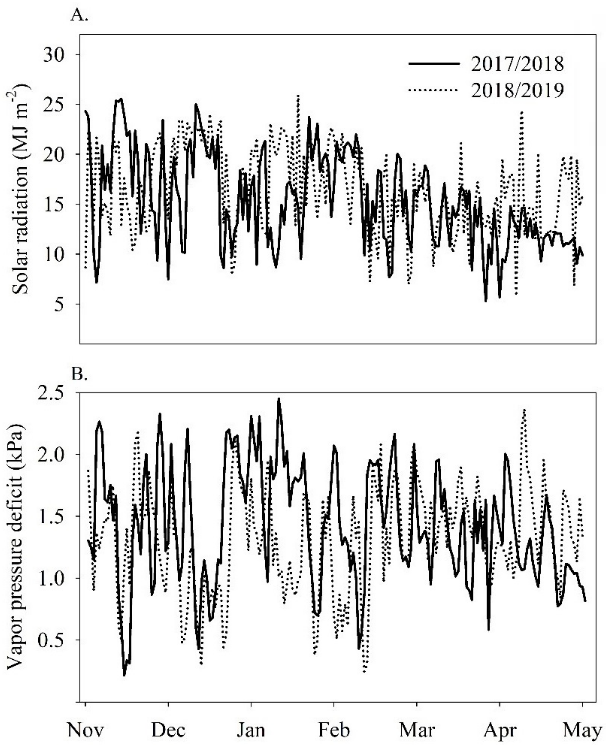



**Figure 2.** Solar radiation (A) and vapor pressure deficit (B) during the cotton growing season in 2017/2018 and 2018/2019

**Table 1.** Chemical attributes of the soil (0-0.20 and 0.20-0.40 m depth) prior to cotton planting

| Soil depth (m) | pH $CaCl_2$ | O.M. (g $dm^{-3}$) | $P_{resin}$ (mg $dm^{-3}$) | H + Al | K | Ca | Mg | CEC | Sand | Clay |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | ($mmol_c$ $dm^{-3}$) | | | | | (g $kg^{-1}$) | |
| | | | | 2017/2018 | | | | | | |
| 0-0.20 | 5.0 | 12.1 | 11.8 | 17.6 | 0.6 | 11.8 | 5.9 | 35.9 | 832 | 146 |
| 0.20-0.40 | 4.7 | 10.0 | 3.4 | 19.6 | 0.4 | 3.7 | 2.9 | 26.6 | 817 | 145 |
| | | | | 2018/2019 | | | | | | |
| 0-0.20 | 5.7 | 14.2 | 11.0 | 15.1 | 1.3 | 49.2 | 17.2 | 82.6 | -- | -- |
| 0.20-0.40 | 5.0 | 10.3 | 6.0 | 18.4 | 1.0 | 19.2 | 5.9 | 44.5 | -- | -- |

O.M. - Organic matter; CEC - Cation exchange capacity

The experimental design consisted of randomized blocks with five replications in a split-plot scheme. Plots were composed of the cultivars with different leaf morphology: Conventional leaf (TMG 47B2RF) and Okra leaf (DBB 509B2RF). Plant densities of 5 (low), 7 (medium), and 9 (high) plants $m^{-1}$ were allocated in the subplots. The plant density was defined based on the official recommendations of the companies that own the cultivars, with a density of 7 plants $m^{-1}$ being recommended. The experiment was carried out under conventional tillage, and the soil remained fallow in the season prior to sowing. The soil was harrowed twice with a heavy harrow and plowed twice with a leveling harrow. Each experimental unit had 21 $m^2$ (3.5 x 6 m) with 1 m between each plot.

The basal dose of fertilizers consisted of 250 kg $ha^{-1}$ of monoammonium phosphate (MAP) (25 and 102 kg $ha^{-1}$ of N and $P_2O_5$, respectively). Topdressing with fertilizers was performed with 120 kg $ha^{-1}$ of $K_2O$ using potassium chloride divided between applications at 30 and 60 days after emergence (DAE) and at 25 and 45 DAE, N fertilization was performed (120 kg $ha^{-1}$ of N). Fertilization was performed manually using conventional urea (45% N).

Four months before planting, 2.5 (2017) and 1.2 (2018) Mg $ha^{-1}$ of dolomitic limestone were applied. In October 2017 and 2018, conventional soil tillage was carried out (heavy harrow 0-0.40 m). Cotton was sown (mechanically) on November 15 (2017) and November 22 (2018), at the density of 13 seeds $m^{-1}$, at a spacing of 0.8 m between rows. At 10 DAE, the number of plants per plot was counted, and plants were thinned to the target density in each treatment. Control of pests, diseases, and weeds, as well as the application of growth regulators, was carried out according to the crop recommendation (Bélot & Vilela, 2020).

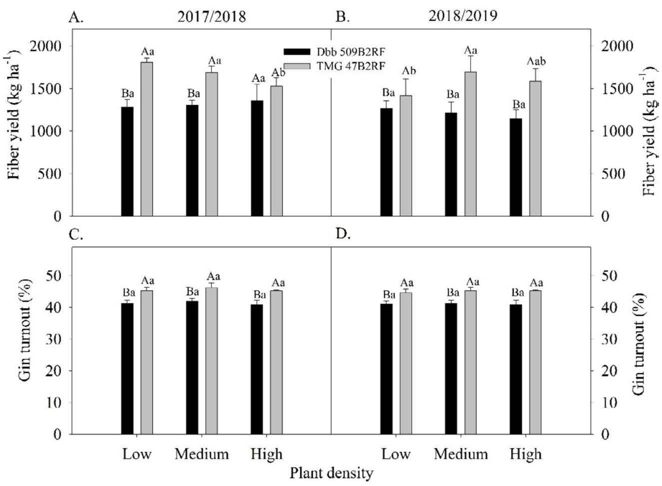
At full bloom (70 DAE), ten cotton leaves (fifth leaf, with petiole) were collected for analysis of nutrient content. After sampling, the leaves were washed in running water, dried in an oven at 65 °C for 48 hours, and ground for macro and micronutrient analysis (Malavolta et al., 1997).

For yield components (boll number and weight) and yield determination, harvesting was performed at 150 DAE by hand-picking bolls from 2 m of each row. A sample (100 g) was ginned for measuring the turnout (ratio between the fiber and cotton seed weights). A subsample (100 g) was used for measuring fiber quality parameters: micronaire, fiber length, fiber strength, fiber maturity, fiber uniformity, and fiber elongation (HVI - High Volume Instrumentals).

After testing for homogeneity and normality, the data were subjected to analysis of variance (ANOVA). Means were compared by Tukey's test with a minimum of 0.05 probability ($p < 0.05$). Sisvar® statistical software was used. Graphs were plotted using Sigmaplot®.

## Results and Discussion

There was an interaction between cultivars and plant density in both seasons. Cultivar TMG 47B2RF produced a 27% (2017/2018) and 29% (2018/2019) higher yield than cultivar DBB 509B2RF (density average) (Figures 3A and B).




Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Vertical bars represent standard errors

**Figure 3.** Fiber yield (A and B) and gin turnout (C and D) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) are affected by plant density (low, medium, and high: 5, 7, and 9 plants $m^{-1}$, respectively), 2017/2018 and 2018/2019 seasons crops

The cultivar DBB 509B2RF showed no difference between plant density for yield and gin turnout (Figure 3). Gin turnout of the cultivar TMG 47B2RF was 10% higher than the cultivar DBB 509B2RF (average of the two seasons) (Figures 3C and D).

The increase in plant density is not directly related to the increase in yield (Khan et al., 2017; Galdi et al., 2022), as shown in the present study (Figures 3A and B). Previously, it was reported that okra leaf cultivars of cotton have greater efficiency in the use of radiation and that increasing plant density increases the interception of solar radiation in okra leaf cultivars (Gonias et al., 2011). However, our findings revealed that density increases do not always result in higher yields (Figure 3A). In tropical climate conditions with high radiation (Figure 2) and a high risk of water deficit (Figure 1), we can obtain equal yield with high and low plant density. However, in most cases, the yield was lower than the conventional leaf cultivar, likely an outcome of the cultivar's genetic potential.

It is important to mention that there is still a tendency to increase plant density to obtain higher yields (Blaise et al., 2021). However, this happens mainly in environments with no water restriction and small-scale plantations. A recent literature review, including studies in arid and low-yield areas, reported that cotton yield is impaired only when plant density is less than 35,000 plants $ha^{-1}$ and that high plant density increases production costs without increasing yield (Adams et al., 2019). Thus, the fact that cotton grows in various production environments around the world leads to this uncertainty about the effect of plant density on yield. We suggest that to evaluate the effect of plant density, the production environment should be considered, taking into account the availability of resources in each environment (water, radiation, temperature, and nutrients).

High rainfall availability (> 1200 mm during the growing season) increases plant height, thus reducing yield (Baio et al., 2019) due to self-shading caused by rank growth, especially at high densities (Figure 3A). High plant density limits light penetration in the canopy and leads to increased abscission of reproductive structures (Echer & Rosolem, 2015) and smaller bolls (Wright et al., 2011; Figure 4C). On the other hand, in years of below-average rainfall, plants under low density cannot produce enough bolls, and under high plant density, there is competition for water, thus decreasing the yield (Figure 3B). Okra leaf cultivars have a greater tolerance to water deficit (Pettigrew, 2004), but, in our study, this characteristic did not translate into higher yield despite the plant density (Figures 3A and B). Conventional leaf cultivars have greater light interception capacity (Heitholt, 1994), resulting in higher yield with adequate adjustment of plant density (Figures 3A and B).

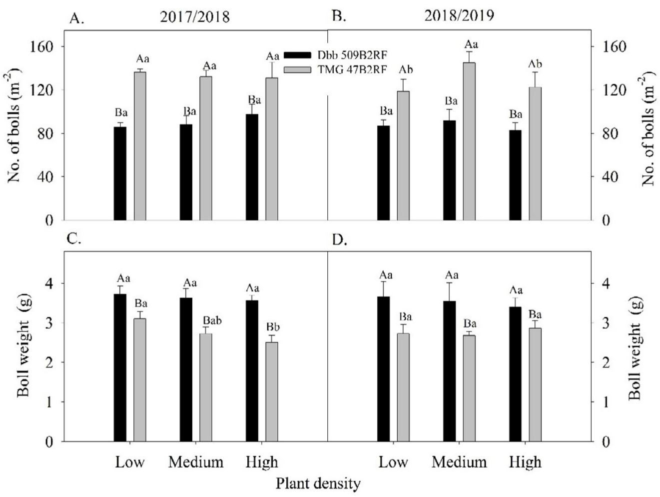
In both cropping seasons, the number of bolls in cultivar TMG 47B2RF was higher than cultivar DBB 509B2RF (Figures 4A and B). In the 2018/2019 season, TMG 47B2RF had the highest number of bolls under medium density (Figure 4B). Boll weight of the cultivar DBB 509B2RF was 23% (2017/2018) and 22% (2018/2019) higher than TMG 47B2RF (Figures 4 C and D).

Okra leaf cultivars of cotton emit bolls above capacity, with greater abscission (Landivar et al., 1983). In our study, we noticed that regardless of the year or plant density, the cultivar DBB 509B2RF (Okra leaf) had the lowest boll number (Figures 4A and B). The lower number of bolls is also associated with soil and climatic conditions, especially in sandy textured soils with low fertility and lower water retention (Usowicz & Lipiec, 2017). Together with the high plant density, these factors resulted in a lower boll number (Figure 4B; Khan et al., 2020b). Furthermore, in years of high rainfall patterns, low plant density can increase the boll weight (Figure 4C). The same does not occur at high density due to self-shading and greater plant growth (Khan et al., 2020a). It was previously reported that there is a high correlation between boll weight and yield, especially in high-yielding crops (Cordeiro et al., 2022). This can be improved by adjusting plant density.

Micronaire of the DBB 509B2RF cultivar showed higher values with low and medium plant density (2017/2018) (Figure 5A). For the other parameters (length and strength), the TMG 47B2RF showed higher values regardless of plant density, except in the 2017/2018 season when the fiber strength of TMG 47B2RF was 4.3% higher under higher plant density (Figures 5E and F).

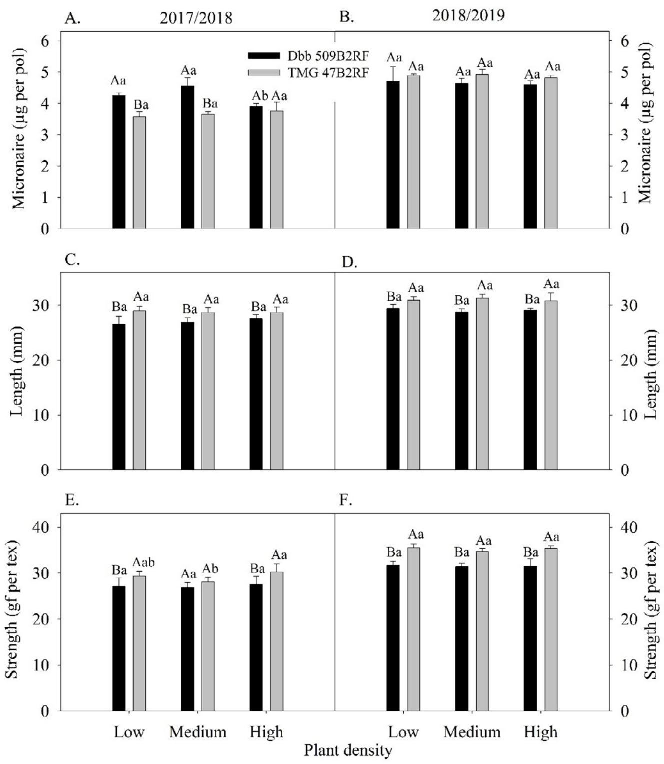
In years with high rainfall, as in the first cropping season (2017/2018), the micronaire was influenced by the cultivar (DBB 509B2RF) and plant density (low and medium) (Figure 5A). The cloudiness and the excessive growth of the cotton (self-shading) reduce the synthesis of carbohydrates, decreasing fiber quality (Echer & Rosolem, 2015), a fact that normally does not occur in years of lower rainfall (Figure 5B). The other parameters were influenced only by the cultivar (TMG 47B2RF) (Figures 5B, C, D, and F), except for fiber strength in the first year (2017/2018), where it responded positively to high density (Figure 5E). In addition, the improvement of fiber quality in crops with lower yield must be considered since the smaller number of sinks increases the availability of carbohydrates for boll filling, which results in improved fiber quality.

The cultivar TMG 47B2RF showed greater fiber uniformity than DBB 509B2RF, regardless of plant density (Figures 6A and B). However, fiber elongation was higher in the DBB 509B2RF cultivar, except in the 2018/2019 season under high plant density (Figures 6C and D). Fiber maturity had little variation between cultivars, but in the second crop season (2018/2019), the medium plant density of cultivar DBB 509B2RF was 1.2% lower than TMG 47B2RF (Figures 6E and F).



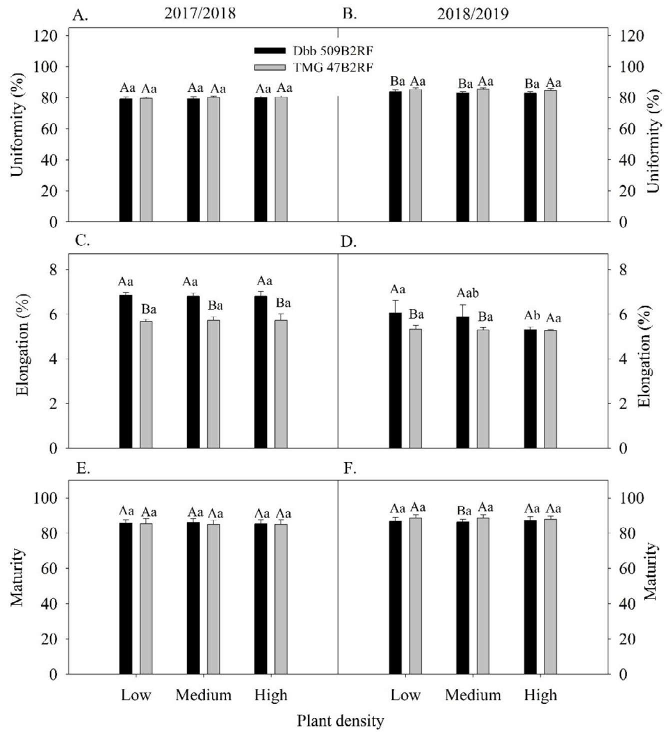

Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 4.** Number of bolls (A and B) and boll weight (C and D) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants $m^{-1}$, respectively), 2017/2018 and 2018/2019 seasons crops



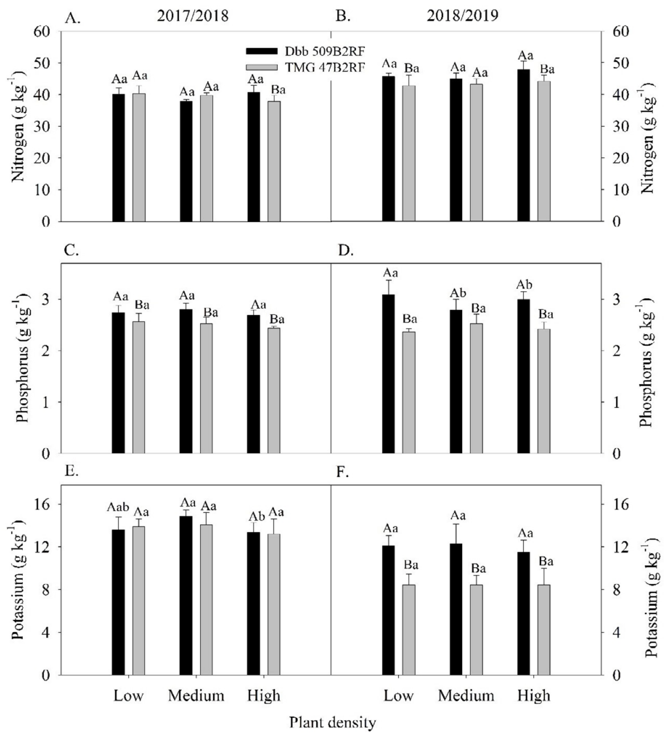

Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 5.** Micronaire (A and B), fiber length (C and D), and fiber strength (E and F) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants $m^{-1}$, respectively), 2017/2018 and 2018/2019 seasons crops




Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 6.** Fiber uniformity (A and B), fiber elongation (C and D), and fiber maturity (E and F) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants $m^{-1}$, respectively), 2017/2018 and 2018/2019 seasons crops




Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 7.** Leaf concentration of nitrogen (A and B), phosphorus (C and D), and potassium (E and F) concentration of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants $m^{-1}$, respectively), 2017/2018 and 2018/2019 seasons

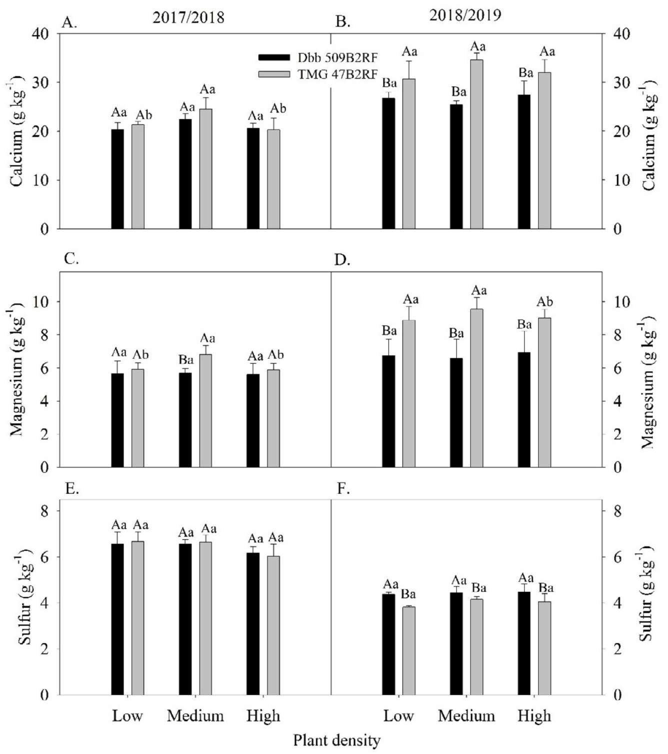
Nitrogen leaf concentration was higher in the cultivar DBB 509B2RF under low (2018/2019) and high plant density (two seasons) (Figures 7A and B). The cultivar DBB 509B2RF showed the highest leaf phosphorus concentration in both seasons (Figures 7C and D). In the 2018/2019 season, the cultivar DBB 509B2RF had the highest phosphorus leaf concentration under low plant density (Figure 7D). Potassium concentration in the first season did not differ between cultivars. In the 2018/2019 season, the cultivar DBB 509B2RF showed a concentration of K 28% higher than the TMG 47B2RF (average plant density) (Figures 7E and F).

Nitrogen concentration in the okra leaf cultivar was below the sufficiency range (Kurihara et al., 2013; Figure 7A). Low light availability can decrease N uptake (Najeeb et al., 2016). This can be accentuated due to self-shading or low irradiance on rainy days. Phosphorus leaf content was positively influenced by the choice of cultivar and in years of lower rainfall and the use of low plant density (Figures 7C and D). However, despite these differences, the phosphorus leaf concentration was classified as sufficient. Potassium leaf content in the first season did not differ between cultivars. In the 2018/2019 harvest, we reported cultivar DBB 509B2RF having a K-content 28% higher than TMG 47B2RF (medium plant density). However, both cultivars showed K-content levels below the sufficiency range (Figures 7E and F).

Calcium leaf concentration was higher in the cultivar TMG 47B2RF (2018/2019), and in the first crop (2017/18), the concentration was higher in the medium plant density (Figures 8A and B). In both seasons, magnesium leaf concentration was higher on cultivar TMG 47B2RF, which showed a lower concentration with high (both seasons) and low (2018/2019) plant density (Figures 8C and D). Sulfur leaf concentration of TMG 47B2RF was higher in the second season (all densities) (Figures 8E and F).

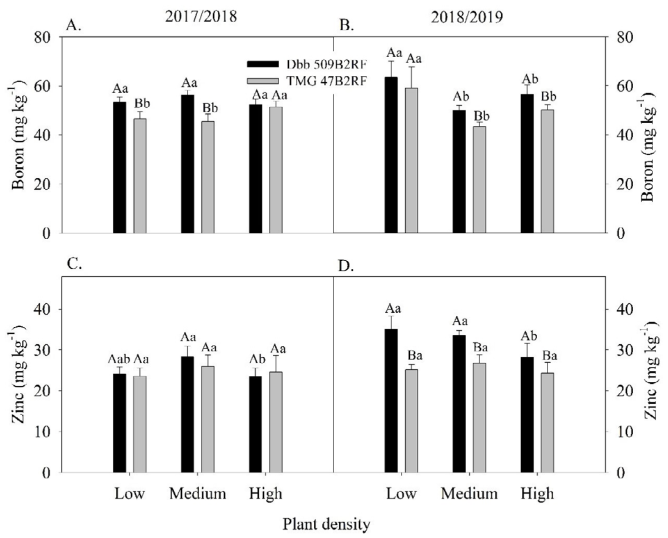
In the first season crop, the calcium leaf concentration in the TMG 47B2RF cultivar was 8.5% higher at medium plant density. The second season crop (2018/2019) was 18.2% higher (average plant density). The magnesium leaf concentration was higher in both season crops in the TMG 47B2RF cultivar, responding positively to medium (2017/2018) and low (2018/2019) plant density. The levels of Ca and Mg increased from one season to the other, this is due to the effect of lime applied in the first cropping season (Table 1). The sulfur leaf concentration was only influenced in the 2018/2019 season crop, being higher in the DBB 509B2RF cultivar, and plant density did not affect leaf S concentration. Even with differences between Ca, Mg, and S concentration in the leaf between cultivars and plant density, all the nutrients had adequate content (Kurihara et al., 2013).

In both seasons, boron leaf concentration was higher in the cultivar DBB 509B2RF (Figures 9A and B). In the 2017/2018 season, TMG 47B2RF showed higher leaf boron concentration under high plant density (Figure 9A). In the 2018/2019 season, both cultivars showed higher leaf boron concentrations under low




Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 8.** Leaf concentration of calcium (A and B), magnesium (C and D), and sulfur (E and F) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants m$^{-1}$, respectively), in 2017/2018 and 2018/2019 seasons crops




Bars with the same lowercase letters do not differ between each other according to the Tukey test ($p < 0.05$). Uppercase letters compare cultivars. Lowercase letters compare plant density. Horizontal bars represent standard errors

**Figure 9.** Leaf concentration of boron (A and B) and zinc (C and D) of cotton cultivars (DBB 509B2RF (okra leaf) and TMG 47B2RF (conventional leaf) affected by plant density (low, medium, and high: 5, 7, and 9 plants m$^{-1}$, respectively), 2017/2018 and 2018/2019 seasons crops

plant density (Figure 9B). While the leaf zinc concentration was 22% higher in DBB 509B2RF (2018/2019), and a decrease was noted under high plant density (two seasons) (Figures 9C and D).

Both cultivar and plant density influenced leaf boron concentration in the second season crop due to the increased organic matter content (Table 1). Regarding the cultivars, only in the 2018/2019 season crop the zinc leaf concentration was higher in the DBB 509B2RF cultivar. However, in the first season crop (2017/2018), the content was higher in the medium plant density and the second season in the low plant density (2018/2019).

## Conclusions

1. The okra leaf cotton cultivar (DBB 509 B2RF) was not a good option to improve cotton yield in sandy soil environments with water restriction, regardless of plant density.

2. The low plant density and the correct choice of the cultivar (TMG 47B2RF) improve fiber yield. However, the best yields are with medium plant density in years of lower rainfall. The fiber quality was more affected by the differences in cultivars, with TMG 47B2RF having a better fiber length and fiber strength while Dbb 509 B2RF has better fiber elongation.

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